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Inverse Normalized Energy Based Feature using Wavelet for Trend Prognosis on Mechanical Coupling for the Common Remotely Operated Weapon Station (CROWS)

by Canh Ly, Andrew Bayba, and Derwin Washington

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Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

In this report, we present an innovated method for diagnosing and predicting loosened bolts on the elevation control motor (ECM) of the Common Remote Operated Weapons Station (CROWS) system in order to prevent a disastrous fault or failure in the gear mechanism that loose bolts could cause. Our method uses the “symlet” wavelet to de-noise non-stationary vibration signals from a tri-axial accelerometer mounted on the ECM. We calculated the ratio of the normalized energy of the “baseline,” in which all the bolts were tightened, to cases in which the bolts were loosened to different levels of torque. The normalized energy signals were calculated from the output of Fast Fourier Transform (FFT) spectral components at the frequency band of the residual signals—the difference between the “raw” experimental data and the de-noised data. We then conducted a series of controlled experiments where we deliberately loosened the ECM bolts to demonstrate the system’s diagnostic and prognostic capability. Based on the experimental data and results from our method, we showed that we can detect a fault and the trend of the loosening bolts on the weapons station. If faults are detected early enough, appropriate measures can be to taken to enhance the reliability of the weapons station.

15. SUBJECT TERMS

Inverse normalized energy, diagnostic, prognostic, CROWS, trend prognosis

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1. Introduction

Engineering systems, such as aircraft, industrial processes, manufacturing systems, transportation systems, electrical and electronic systems, etc., are becoming more complex and are subject to failure modes that adversely impact their reliability, availability, safety, and maintainability. Such critical assets are required to be available when needed, and thus must be maintained on the basis of their current condition rather than on the basis of scheduled or breakdown maintenance practices. Moreover, online, real-time fault diagnosis and prognosis can assist the operator in avoiding catastrophic events (Ly et al., September 2009). Recent advances in Condition-Based Maintenance and Prognostics and Health Management (CBM/PHM) have prompted the development of new and innovative algorithms and advanced architectures (Ly et al., August 2009) for fault, or incipient failure, diagnosis and failure prognosis aimed at improving the performance of critical systems.

We present an innovated method for diagnosing and predicting loosened bolts on the elevation control motor (ECM) of the Common Remote Operated Weapons Station (CROWS) system. Our method uses a “symlet” wavelet, one of the built-in functions in the MATLAB Wavelet Toolbox, to de-noise nonstationary vibration signals from a tri-axial accelerometer mounted on the ECM. Then, we calculate the ratio of the normalized energy of the “baseline,” in which all bolts are tightened, to cases in which the bolts are loosened at different levels of torque. Finally, we determine the inverse normalized energy signals from the output of Fast Fourier Transform (FFT) spectral components at a frequency band of the residual signals—the differences between the “raw” experimental data and the de-noised data. Further, we conduct a series of controlled experiments where we deliberately loosen the ECM bolts to demonstrate the system’s diagnostic and prognostic capability. Based on the experimental data and results from our method, we show that we can detect both faults and the trend of the loosening bolts on the CROWS.

Section 2 outlines the CROWS data acquisition. Section 3 provides the description of the inverse normalized energy algorithm. Section 4 gives the results of the experimental data performed on the CROWS S/N 071 (URM-1 configuration).

2. CROWS Data Acquisition

The U.S. Army Research Laboratory (ARL) uses the CROWS as a test bed to perform prognostics and diagnostics (P&D) on Army assets. Using the CROWS, ARL has evaluated sensors, data collection and transmission techniques; accelerated testing methodologies; and developed P&D algorithms and hardware (Bayba et al., 2010). In March 2009, we performed a series of controlled experiments on the CROWS where we systematically and gradually loosened bolts securing critical components of the system. These experiments can be considered a form of accelerated testing, in which data show various levels of “damage.” Damage here is defined as degradation in bolt tightness (torque) that will eventually lead to system failure.

The CROWS is a two-axis stabilized weapons system remotely operated using a joystick or programmed scan cycle. The specific unit under test was a CROWS S/N 071 (URM-1 Configuration). The system had a M2 0.50 cal machinegun mounted. The system did not have the add-on armor plating typically in place on a fielded system. Table 1 contains the nomenclature/identification/serial numbers from the unit under test. From our viewpoint the system is composed of four primary subunits:

- *Pedestal Assembly:* The pedestal assembly is the main compartment to which virtually everything else is mounted. It receives and distributes electrical power and control, and houses the azimuth motor and control electronics; the sensor unit motor and control electronics; and the control electronics for the gun actuator.
- *Elevation Unit:* The elevation unit houses the elevation control motor and motor control electronics. It mounts to the pedestal assembly.
- *Sensor Unit (SU):* The SU houses the video and thermal imaging hardware and the laser rangefinder. It mounts to the pedestal assembly.
- *Gun/Actuator Assembly:* The gun/actuator assembly includes the gun, gun mounting cradle with firing mechanisms, and a linear actuator whose action arms the gun and pulls the trigger. It mounts to the pedestal assembly.

Table 1. CROWS system 1 identifiers.

Assembly	**Unit Marking/Nameplate**
Complete CROWS unit	Stabilized Remote Weapon System PN 21677-0200-011 Rev E S/N: 071 Cage 11871
Subassembly	
Pedestal assembly	Pedestal Assembly PN 21677-1000 Rev F S/N: 071
SU	Fire Control Systems PTY LTD S/N: AA4183 Ref No ASY06077 EFCS-T Sensor Unit Cage Z5731
Elevation control unit	Elevation Bar Code 21677-3000-00 00086
Gun/actuator assembly	Electric Cylinder Model 12-0342 S/N: 03122A113631 OPTCODER Type: LDA-185-1000CE IDC P/N 802-002

Note: Unit markings/nameplate information was recorded from the actual assembly components.

2.1 Data Collection Hardware and Software

This section describes CROWS data acquisition system (figure 1). The CROWS data acquisition system includes the CROWS system (weapons platform), described below; an eDAQ digital signal collector; sensor modules, described details in appendix A; tri-axial accelerometers; and a personal computer. The weapons platform was the unit under test monitored via the accelerometers. The accelerometers received the vibration signals at four locations—elevation control unit, pedestal assembly, gun/actuator assembly, and sensor units. These locations are described in detail in sections 2.2.

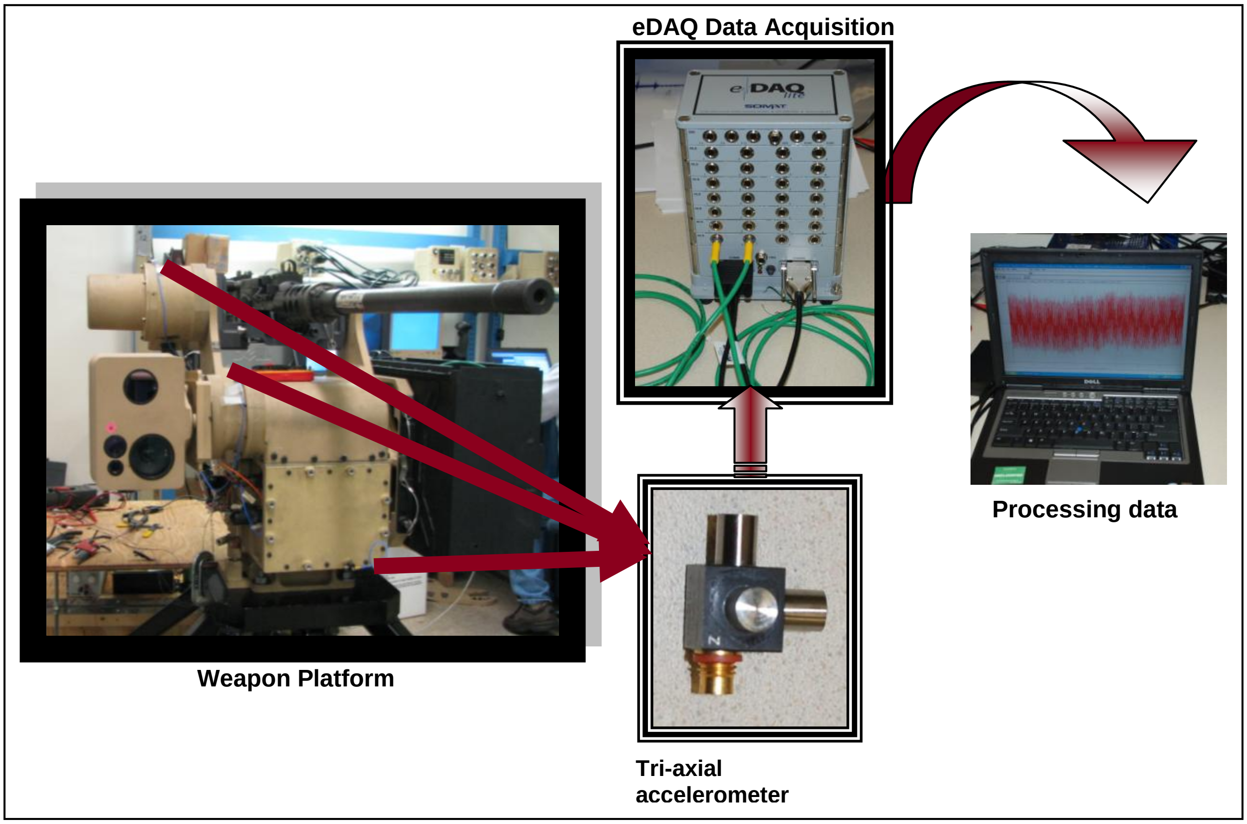

Figure 1. CROWS data acquisition system.

Data collected during this set of tests involved various sensors and data acquisition hardware and software. Vibration within the system was the primary parameter of interest. Various voltages, currents, and temperatures were recorded to supplement the vibration data. Vibration data were acquired through the use of four tri-axial accelerometers (Vibra-metrics model 3000). The data acquisition system that provided the collection and storage was the SoMat eDAQ-lite System. Unless otherwise noted, all data acquisition hardware and software were products of HBM, Inc. The eDAQ-lite was controlled by a laptop computer, a Dell Latitude D620, using the program TCE v3.11.0, build 227. The software used to upload data to the laptop computer and parse it was Infield v2.1.0. Power for and signal conditioning of each accelerometer was provided by EICP-B modules.

Data were collected by sampling the output of the sensors while the weapons system continuously cycled through a set of programmed movement operations (figure 2). In figure 2, the lines shown should be viewed as the trace of the gun muzzle in three-dimensional (3-D) space. As can be seen, the movement incorporated both rotations in azimuth and elevation, as well as a combined rotation in azimuth and elevation.

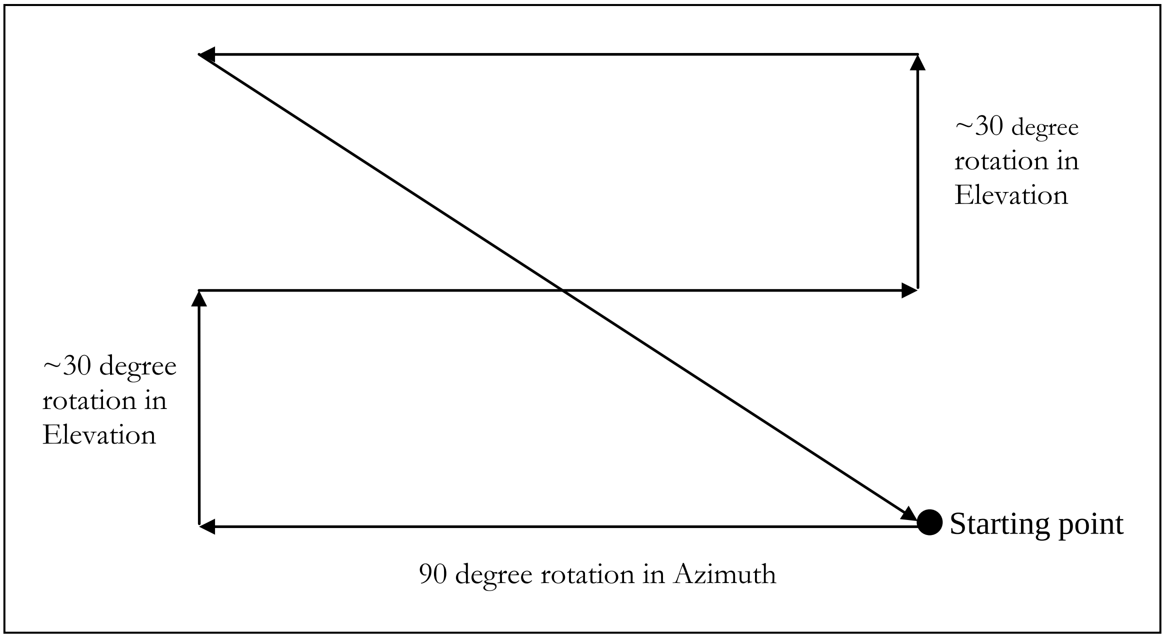

Figure 2. Movement of one cycle of the weapons system.

For ARL reference purposes, we arbitrarily assigned an orientation to the system that can be described as the perspective of an observer at the "rear" of the system looking outward toward the "front." Specifically, the front is the normal firing direction of the gun with the SU and elevation unit on the "right" and the ammo box on the "left." A further delineation between "front" and "rear" is that the power and control cabling enters the main compartment of the system from the "rear."

2.2 Accelerometer Mounting

Each of the four subassemblies had one accelerometer attached to it. Figures 3–7 show the general placement of accelerometers on system. Details of the mounting locations are as follows:

1. *SU*: The attachment is at the junction of the SU and pedestal assembly, specifically on a flange in the closest possible proximity to the SU harmonic drive gearing (figure 3). The attachment was accomplished by inserting an ARL-fabricated extension at one of the flange mounting points. This extension placed the accelerometer ~½ in away from the center of the screw mounting point. Accelerometer axis orientation: X is up, Y is rear, and Z is right.

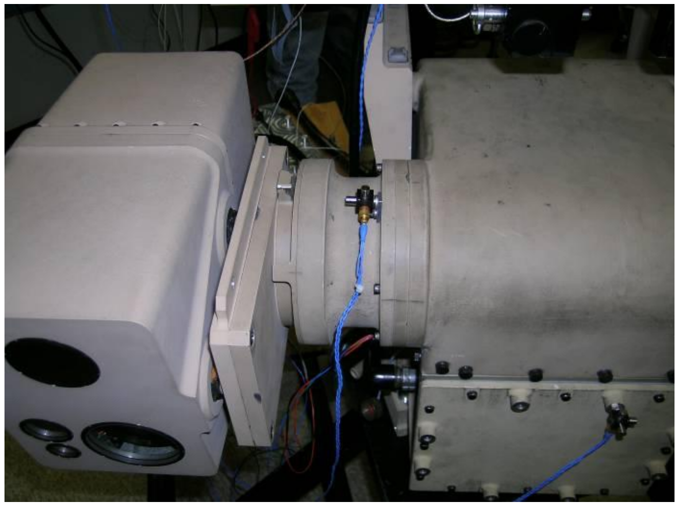

Figure 3. Accelerometer mounting position on the SU.

2. *Gun/Actuator Assembly*: The attachment is at the mounting location of the linear actuator to the gun cradle, specifically by replacing the upper right mounting screw (one of four mounting screws) with a custom ARL thread adaptor bolt (8-32 to 10-32) (figure 4). The first number of the bolt is the largest (major) diameter of the bolt and the second number is the number of threads per inch. For example, the major diameter in unified threads is defined as (0.060 in + 0.013 in × (numbered diameter)). So #8 has a major diameter of 0.164 in. The accelerometer mounts directly to the 10-32 thread of this adaptor placing it inline with the original mounting screw. The goal of this accelerometer was to pick up vibrations in the cradle. Accelerometer axis orientation: X is rear, Y is down, and Z is right.

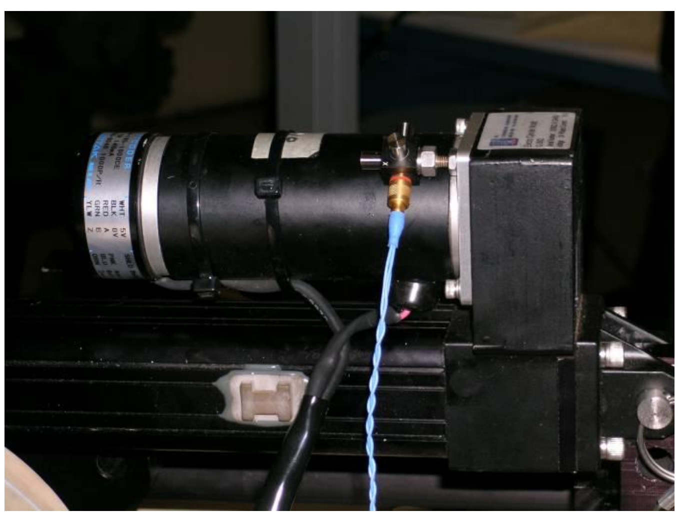

Figure 4. Accelerometer mounting position on the Gun/Actuator Assembly.

3. *Pedestal Assembly*: The attachment is at the bottom front right 1/4-28 (1/4 in major diameter with 28 threads per inch) hole in the lower compartment “front” cover plate

(facing the plate) (figure 5). This location is one of eight heavy-up armor attachment points on this plate. The accelerometer was attached using a custom ARL thread adaptor bolt (1/4-28 to 10-32). Accelerometer axis orientation: X is up, Y is right, and Z is front.

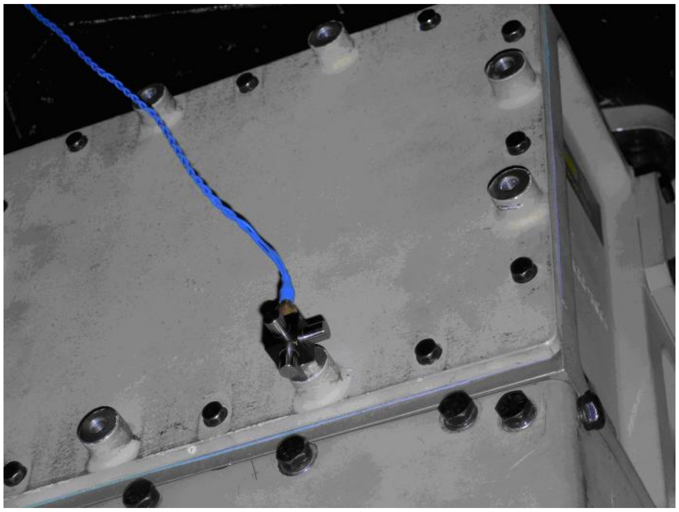

Figure 5. Accelerometer mounting position on the pedestal assembly.

4. *Elevation Control Unit*: The attachment is at the top right 10-32 existing hole in the bell housing of the elevation drive motor (figure 6). This was a direct attachment, thus no adaptors were necessary. This location was chosen because it produced the highest amplitude signal upon elevation in earlier testing. Accelerometer axis orientation: X is left, Y is rear, and Z is up.

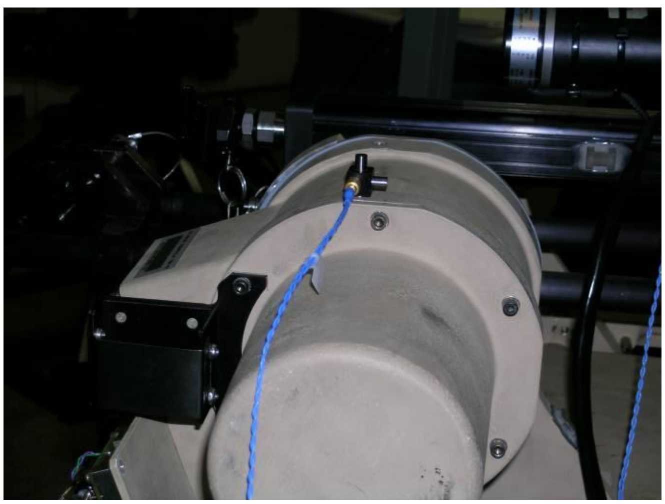

Figure 6. Accelerometer mounting position on the elevation control unit.

3. Inverse Normalized Energy Algorithm

Figure 7 shows a flowchart of the Inverse Normalized Energy Algorithm. The algorithm starts off with the input vibration data collected with an acquisition system, as described in section 2. Since the accelerometer had a very slow frequency response and unwanted noise sources due to other parts of the CROWS systems, the one-dimensional de-noising techniques (MATLAB Wavelet Toolbox, User's Guide, version 3) were used to extract out the unwanted noises and unnecessary responses. Many de-noised techniques have been introduced in open literature (Daubechies, 1992; Donoho, 1995; Mallat, 1989) and many routines have been developed in the MATLAB toolbox. The effect of each de-noising technique has minimum impact on the result. In this report, the "symlet" wavelet package method at the level 5, one of the built-in functions in the MATLAB Wavelet Toolbox, was used to de-noise signals. The de-noised signals were then subtracted by the input data to obtain the residual data. The energy spectrum of each data file was computed. The frequency spectrum covers from zero to half of the sampling frequency, in this case, 20 KHz. Each spectrum was examined at different bands. It turned out the band was selected when the energy spectrum changed. For this particular case of the mechanical coupling on the CROWS, we selected a frequency band of 7.1–7.2 KHz. The maximum spectral component was extracted out for each file at the selected frequency band. Then, we calculated the inverse normalized energy: the inverse ratio of the normalized energy of the baseline, in which all bolts were tightened, versus the cases when bolts were loosened at different levels of torque.

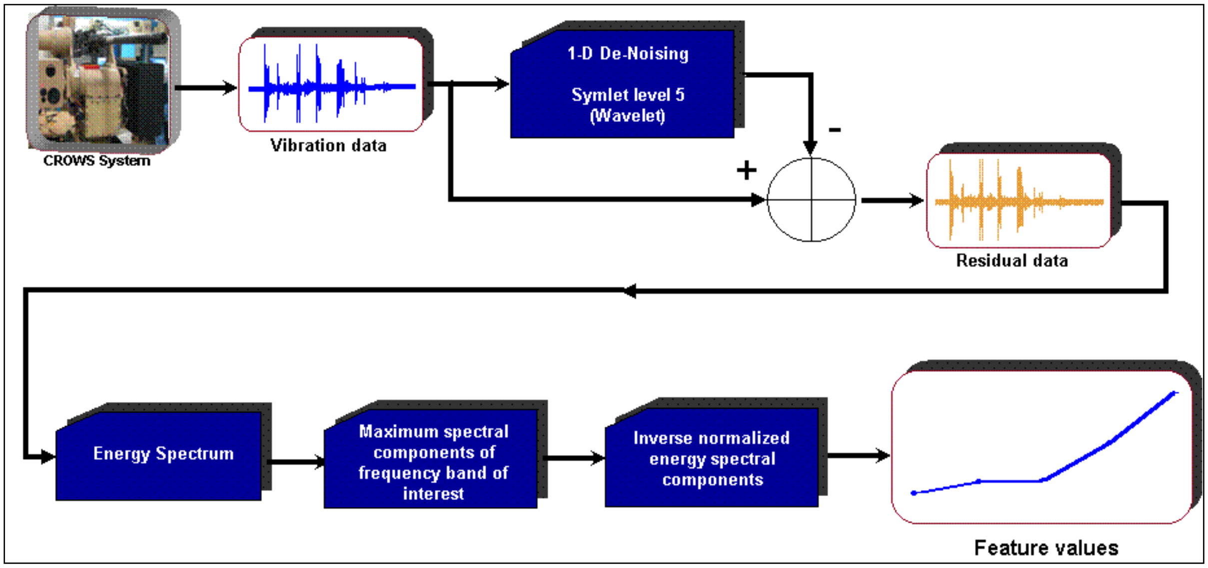

Figure 7. Flowchart of Inverse Normalized Energy Algorithm.

The values of the ratios are the feature values for the fault diagnostic. The trend of the fault diagnostic profile shows the progress of loosening bolts as the torque of the bolts on the ECM were decreased from totally tightened to loosened hand tight. Mathematically, the feature values, FV, are calculated as follows:

$$\mathrm{FV}(i) = \frac{1}{\dfrac{\underset{f_B \subset f}{\mathrm{Max}}\left[\left\{ FFT(R_b)|_{f_B} \right\}^2 \right]}{\underset{f_B \subset f}{\mathrm{Max}}\left[\left\{ FFT(R_i)|_{f_B} \right\}^2 \right]}} \qquad \text{where } i = 1, 2, 3, 4 \tag{1}$$

where, *FFT* is Fast Fourier Transform with the FFT size of the length of the data record. The vertical line (|) in equation 1 means that the $(\bullet)$ operand is evaluated at the certain condition. f_B is the frequency band of interest, in this case, f_B = [7.1–7.2 KHz]. f is a set of frequency [0–20 KHz]. R_b is the residual signal (unit in g (gravity)) of the baseline data. R_i is the residual signal (unit in g) of the data at the level of torque i.

4. Results

We recorded data from the tri-axial accelerometer mounted on the ECM. While the accelerometer has three different axes, we chose to use only one axis (the *y*-axis) for the analysis for this report. Since the analysis for other axes was similar to that of the *y*-axis, it was not included in this report.

The bolts of the ECM were deliberately changed at five different levels. Figure 8 shows the "raw" data of the CROWS, amplitude (g) versus time (s). At the first level, all bolts were completely tightened to ~54 foot-lb (ft-lb), shown as Baseline. At the second level, the torque of the bolts was decreased to 34 ft-lb, shown as Run #1. At the third level, the bolts were loosened at 25 ft-lb, shown as Run #2. At the fourth level, the bolts were loosened at the torque of hand tightened and less than 25 ft-lb, shown as Run #3. At the last level, the bolts were completely loosened, shown as Run #4. The length of each data file was recorded for 30 s and the data were sampled at 20 KHz. Each data file was recorded for a complete full cycle, as shown in figure 2.

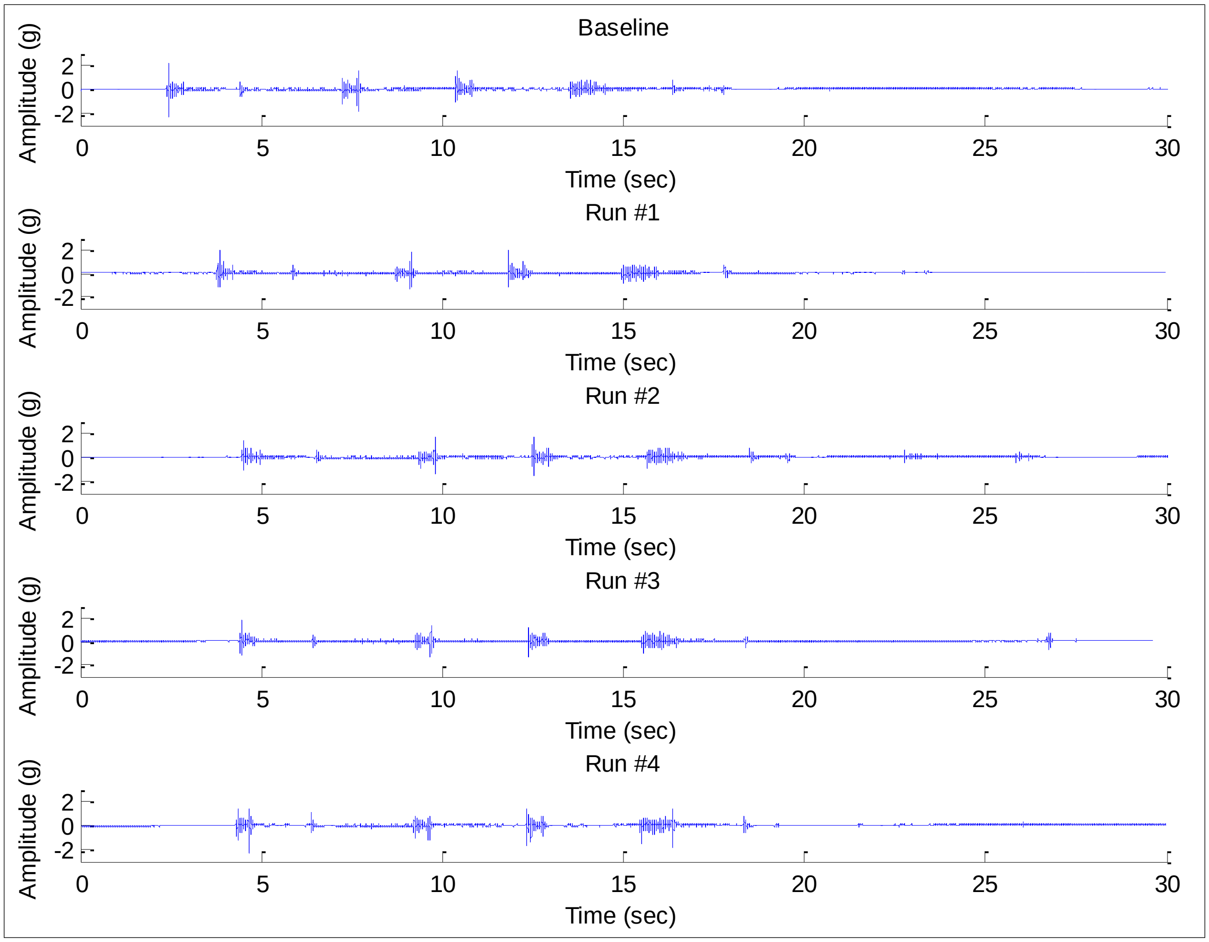

Figure 8. Raw data.

Figure 9 shows the de-noised signals of the raw data via 1-D de-noising technique using the symlet wavelet at the level 5 of the decomposition. As shown in figure 9, the unwanted noises and other signals were extracted. Since the collected data included a combination of signal and noise, de-noising was used to remove the unwanted noise and thus improve the signal-to-noise ratio and also remove the low frequency modulation of the accelerometers.

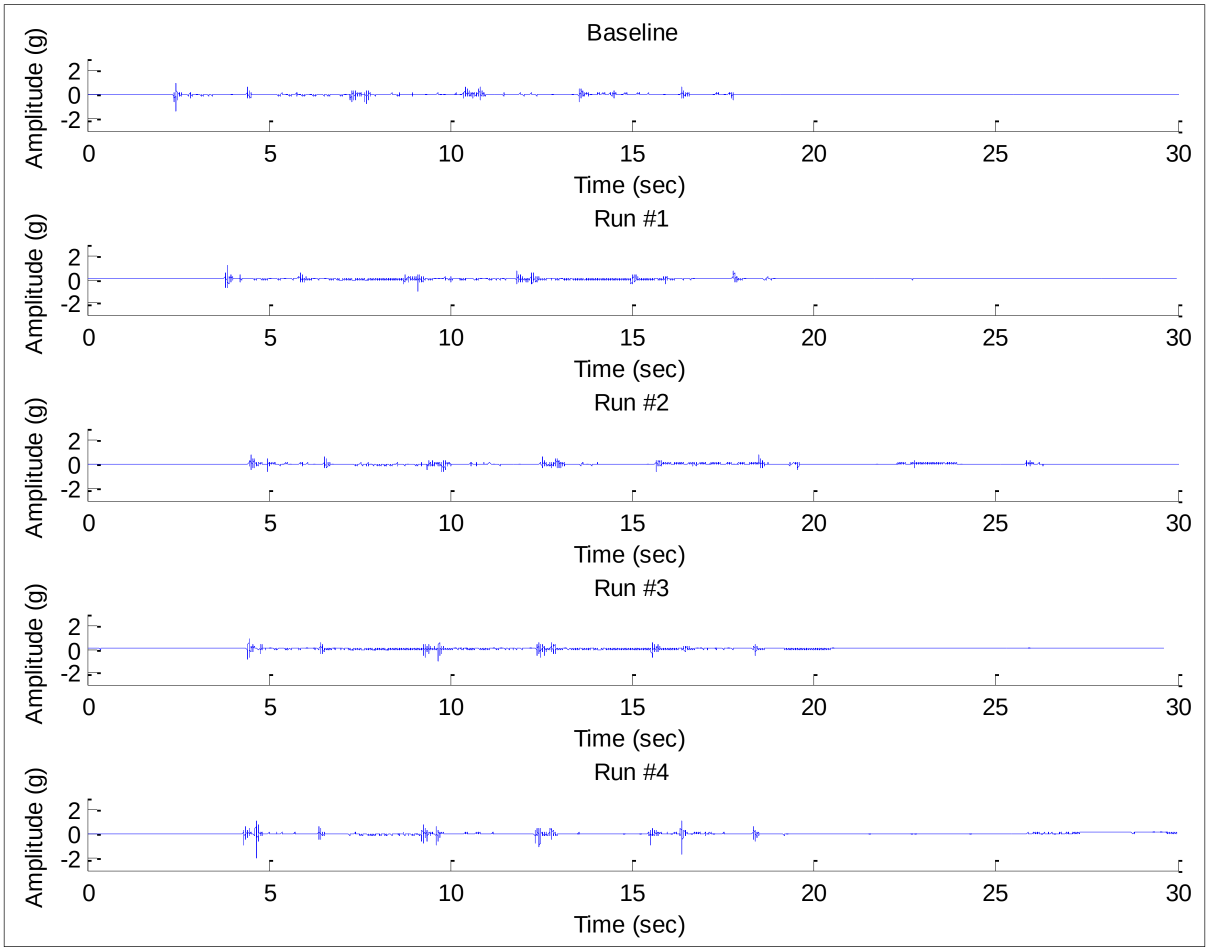

Figure 9. De-noised signals.

Once the signals are de-noised, the residual signals, as shown in figure 10, were computed by subtracting the de-noised signals (figure 9) from the raw data (figure 8). These residual signals were then used to calculate the feature values. Figure 11 shows the energy spectra of the baseline and the individual runs. For figure 11, we selected the frequency band of interest, 7.1 to 7.2 KHz, to compute the inverse normalized spectra using equation 1. Other frequency bands were also used for the computation; however, the results for those frequency bands were not significantly different for different runs. The feature value plot is shown in figure 12. As the torque for the tightened bolts decreased, the inverse normalized energy (or feature) values increased. This indicates that the inverse normalized energy algorithm can detect the fault of loosened bolts on the ECM of the CROWS.

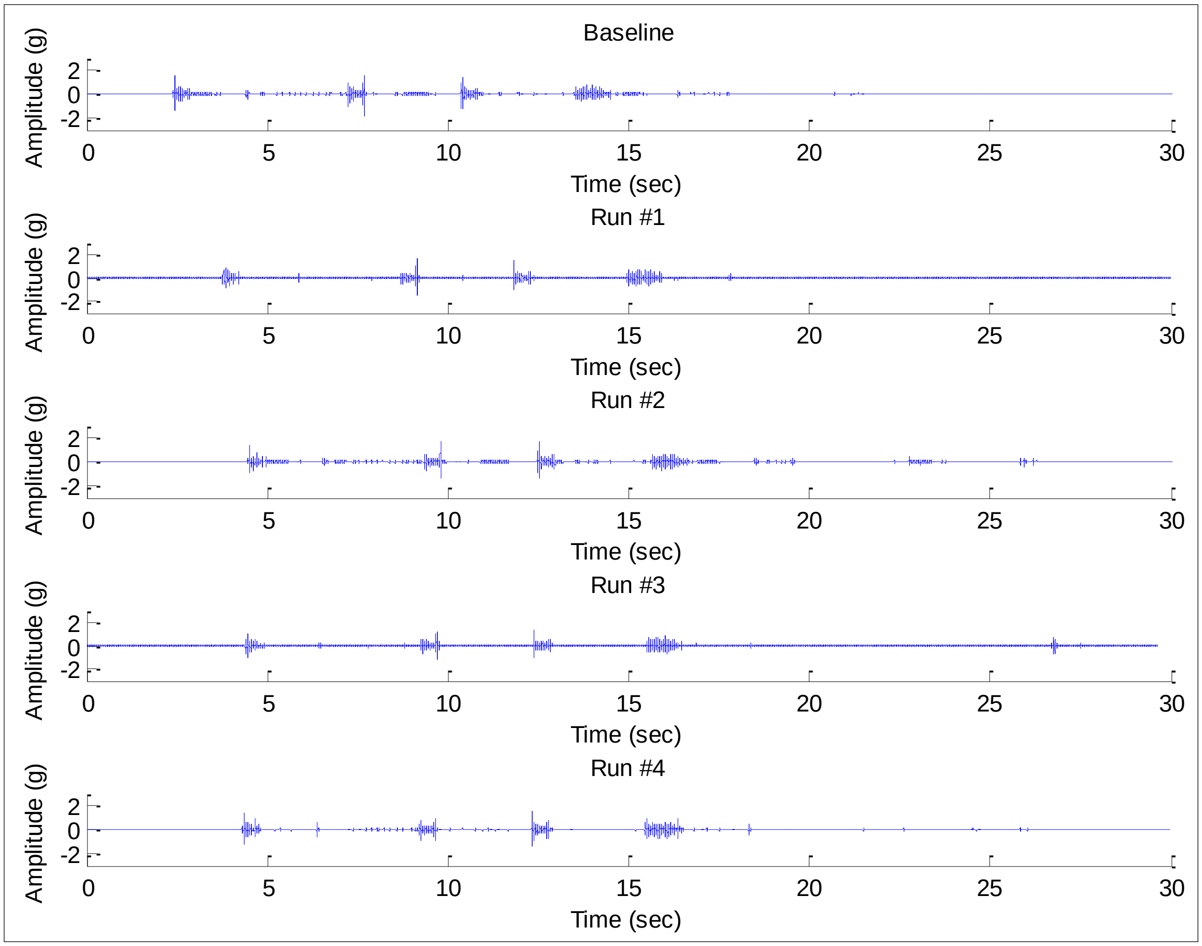

Figure 10. Residual signals.

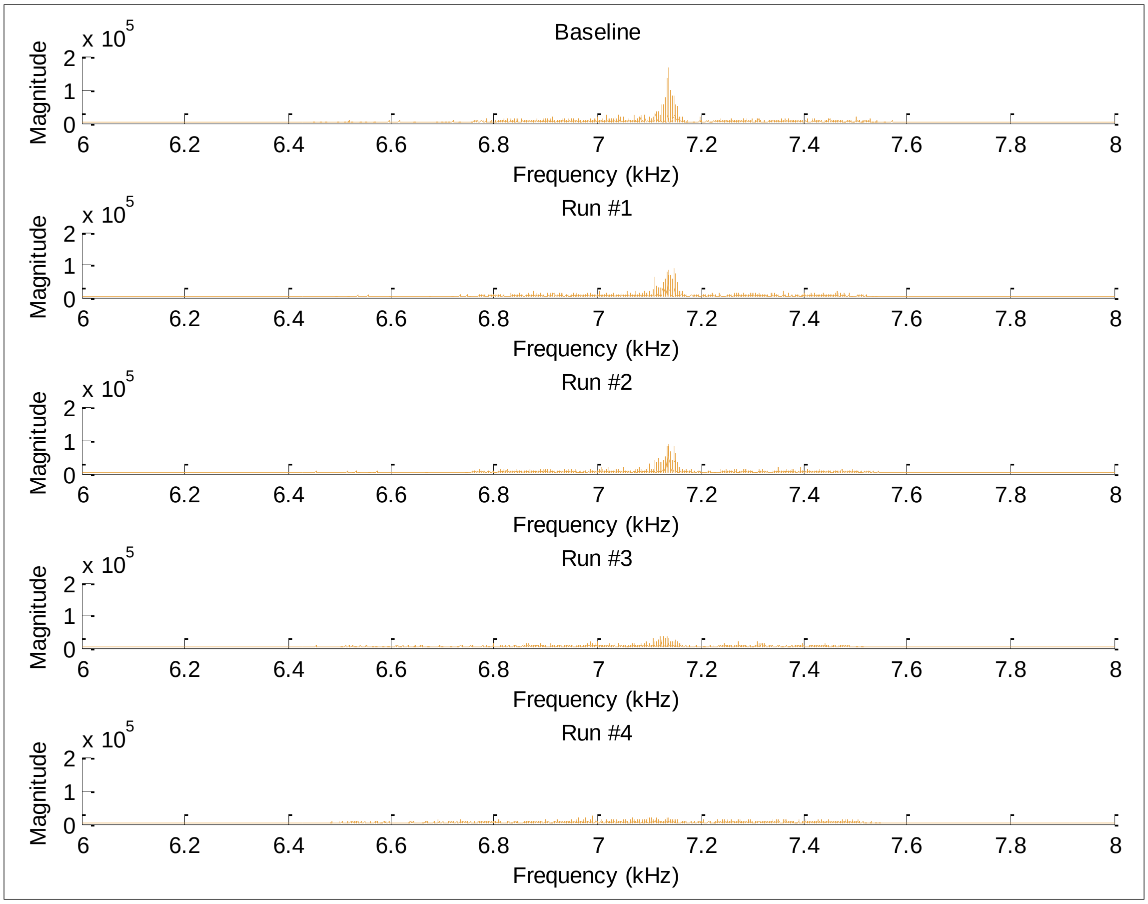

Figure 11. Energy spectra.

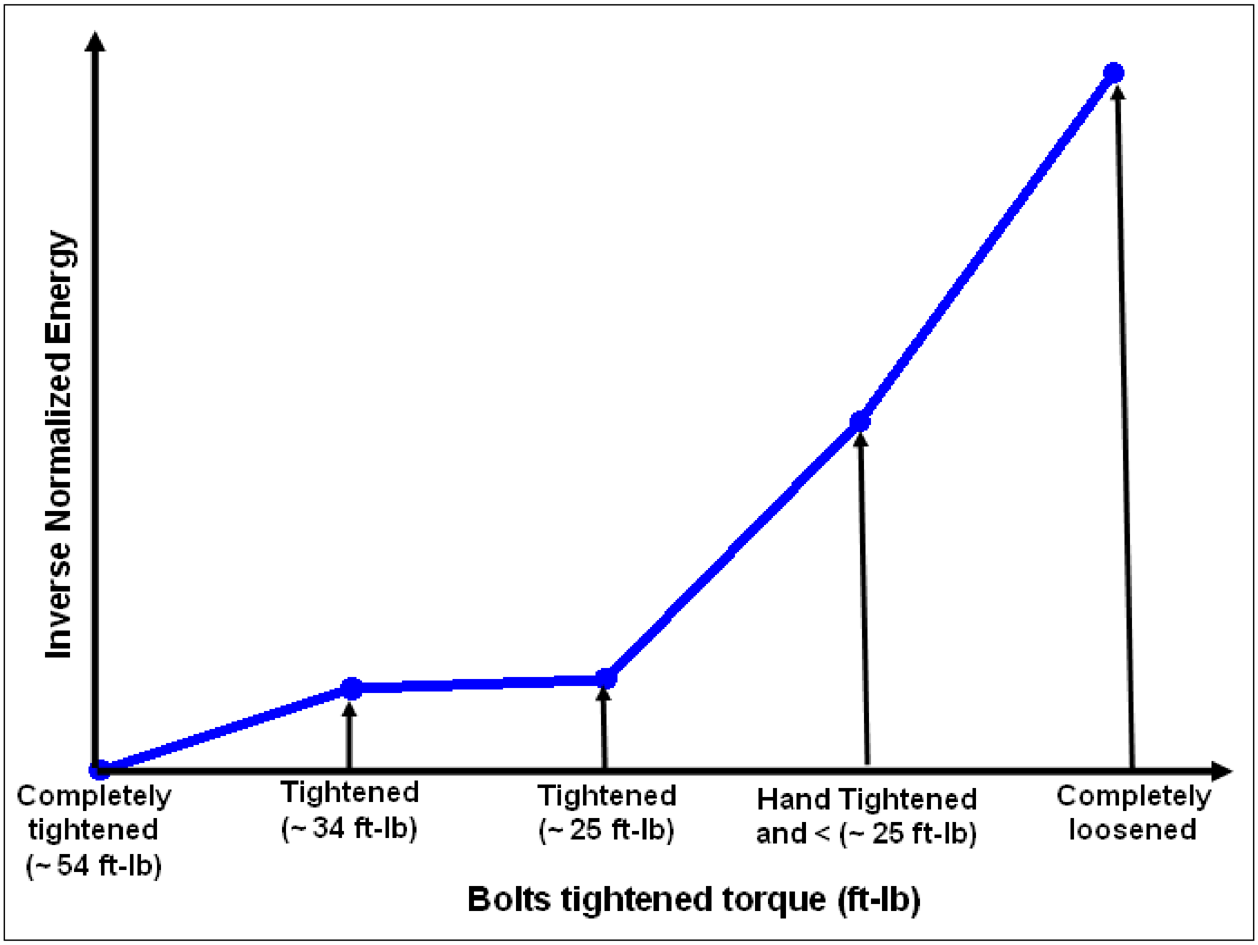

Figure 12. Feature values.

5. Conclusion

We have developed an innovated method for diagnosing and predicting loosened bolts on the ECM of a CROWS. The methods uses an algorithm based on features using a wavelet family package for fault detection and trend prognosis on mechanical coupling in the CROWS. In particular, the method computes the inverse normalized energy via de-noising techniques using the symlet wavelet package. In this effort, we applied the algorithm to the experimental data. The results indicated that the algorithm was robust—it was able to detect loosened bolts on the CROWS as well as on other mechanical systems.

6. References

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Appendix A. Instrumentation Specifications

The following is a short description of the hardware and sensors used during this data collection.

A-1 SoMat eDAQ-lite

The SoMat eDAQ-lite (figure A-1) is a standalone data acquisition system. The system is built of several data aquisition layers. The configuration of the SoMat eDAQ-lite used for this study is composed of the base processor layer (ELCPU), a battery layer (ELBAT-2), seven simultaneous high level layers (ELHLS), and a digital input/output layer (ELDIO). The ELHLS layers contain the channels used for data collection in this series of experiments; each provides four simultaneously sampled high-level differential analog inputs through independent connectors.

Physical

Size:	6.875 in W x 5.625 in L x 8.75 in H
Temperature:	–20 to 65 °C
Connectors:	SoMat 6-Pin M8

Enclosure

Sealed System:	Machined aluminum case and sealed gaskets protect the system from humidity, corrosion, water spray, and dust.
Vibration Tested:	Swept sine tested from 5 to 2000 Hz at 20 G's
Modular:	Up to eight layers can be custom configured pending testing requirements. Four screws are all that is required to disassemble a system.

System

Input Power:

ELCPU:	10-18 VDC
Fuses:	10A, automotive mini-blade

Internal backup battery

Sample Rates:

Master Clock Rates:	100 kHz = 0.1 Hz to 100 kHz
	98.3 kHz = 0.1 Hz to 98,304 Hz

Communications

Ethernet:	100 BaseT
Serial:	RS232 up to 115,200 baud

Memory

2 GB Internal Flash

64 MB Internal DRAM

Figure A-1. SoMat eDAQ-lite.

A-2 ICP-Type Signal Conditioning Module (EICP-B)

This module (figure A-2) supplies a regulated 4-mA current source to an Integral Electronics Piezoelectric (IEPE) transducer. Constant current biased transducers require AC coupling for the output signal. The ICP-Type Signal Conditioning Module uses a 1 microfarad–1MΩ coupling network, which forms a 0.159-Hz high pass input filter. That is, a sinusoidal input signal at 0.159 Hz will be attenuated by 3 dB, (output signal at 70.7% of input). Frequencies below 0.159 Hz will be attenuated more, higher frequencies less.

Physical

Size:	0.75 in W x 3.25 in L x 0.75 in H (1.905 cm W x 8.255 cm L x 1.905 cm H)
Weight:	0.08 lbs (0.03 kg)
Temperature:	–20° to 65° C
Connectors:	SoMat 6-Pin M8 and BNC

Inputs

Input Power: 24 VDC at 4 mA

Load: 1 MΩ

Figure A-2. EICP-B.

A-3 SoMat Thermocouple SMART Module (SMITC)

The SMITC (figure A-3) provides isolated thermocouple conditioning with software selectable linearization tables for J-, K-, T-, and E-type calibrations. The module has universal cold junction compensation and is fully isolated to 500 V.

Figure A-3. SMITC.

A-4 K Type Thermocouple

The K Type Thermocouple has the following specifications:

- Surface mount with self-adhesive backing
- Better than 0.3 s response time
- 2 m (72 in) color-coded perfluoroalkoxy (PFA) insulated leads
- Rated to 175 °C (350 °F) long term

A-5 Vibra-Metrics Model 3000 Tri-axial Accelerometer

The Vibra-metrics model 3000 tri-axial accelerometer (figure A-4) has the following specifications:

Sensitivity: at 100 Hz, ±5% 10 mV/g, 1.02 mV/(m/s2)

Frequency Range:

- ±5% 3 Hz, 0.7 kHz
- ±10% 2 Hz, 0.8 kHz

- ±3 dB 1 Hz, 0.10 kHz

Turn-on Time: 2% of final bias <5 s

Amplitude Range: at 72 °F ±500 g

Mounted Resonance: >25 kHz

Transverse Sensitivity: <5%

Figure A-4. Vibra-Metrics model 3000.

A-6 Electrical

Noise (typical):

- Broadband 2.5 Hz to 25 kHz 1500 µg (rms)
- Spectral 10 Hz 100 µg/√Hz
- 100 Hz 25 µg/√Hz
- 1000 Hz 10 µg/√Hz

Output Impedance: 1000 Ω

Isolation: >100 Meg Ω

Noise Rejection: (EMI/RFI) >52 dB

Bias Volts (nominal): 7 VDC

Power Requirements: 15–30 VDC

Current Regulating Diode: 1–6 mA

A-7. Environmental

Temperature Range: –40 to 250 °F / –40 to 121 °C

Base Strain: <0.005 g peak/µstrain

Shock Limit: 5000 g

A-8 Physical

Physical Dimensions:

- 8 in h x 0.8 in w x 1.05 in d
- 2 cm x 2 cm x 2.7 cm

Weight: 0.35 oz/10 g

Case Material: Titanium

Mounting: 10-32 removable stud

Mounting Torque: 20 in-lb (2.2 N-m)

Connector: Side 4-pin

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
CBM/PHM	Condition-Based Maintenance and Prognostics and Health Management
CROWS	Common Remote Operated Weapons Station
ECM	elevation control motor
FFT	Fast Fourier Transform
P&D	prognostics and diagnostics
PFA	perfluoroalkoxy
SU	Sensor Unit

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1	COMMANDER US ARMY RDECOM ATTN AMSRD AMR W C MCCORKLE 5400 FOWLER RD REDSTONE ARSENAL AL 35898-5000
2	US ARMY RDECOM-ARDEC ATTN RDAR WSF A P JONNSON ATTN RDAR WSF A G GARCIA BLDG 91 PICATINNY NJ 07806
2	US ARMY RDECOM-ARDEC ATTN RDAR WSF A S GEARHART BLDG 91 ATS PICATINNY NJ 07806
1	US ARMY RDECOM-ARDEC ATTN RDAR WSF A D MARSTON BLDG 61S PICATINNY ARSENAL NJ 07806-5000
1	US GOVERNMENT PRINT OFF DEPOSITORY RECEIVING SECTION ATTN MAIL STOP IDAD J TATE 732 NORTH CAPITOL ST NW WASHINGTON DC 20402
1	US ARMY RSRCH LAB ATTN RDRL CIM G T LANDFRIED BLDG 4600 ABERDEEN PROVING GROUND MD 21005-5066
8	US ARMY RSRCH LAB ATTN IMNE ALC HRR MAIL & RECORDS MGMT ATTN RDRL CIM L TECHL LIB ATTN RDRL CIM P TECHL PUB ATTN RDRL SER E A BAYBA ATTN RDRL SER E C LY ATTN RDRL SER E D WASHINGTON ATTN RDRL SER E K TOM ATTN RDRL SER E R DEL ROSARIO ADELPHI MD 20783-1197

TOTAL: 21 (1 ELEC, 1CD, 19 HCS)

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